DESIGN OF INTEGRATED MODE S TRANSPONDER, ADS-B AND DISTANCE MEASURING EQUIPMENT TRANSCEIVERS

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Abstract

This work is devoted to the design of an analog transceiver for the Aeronautical Radio Navigation Services band (960 to 1215 MHz) as a required step to the exploitation of the Software Defined Radio concept in avionics. The integration of all the equipment operating in this band into a single piece of reprogrammable hardware minimizes the size, weight, power and cost (the so-called SWaP-C requirements) of avionic equipment, as well as it enables easy and fast transition towards a modernization of the Communications, Navigation and Surveillance standards. The main challenges of the design are: To provide the receiver with the dynamic range required by the Minimum Operational Performance Standards; to minimize the SWaP-C requirements by sharing a single High Power Amplifier for all the services specified in the title; and to establish a suitable duplexing technique that allows all the services to meet their operational goals. Along with this design, an operational study of the proposed multiplexing/duplexing schemes is carried out through software simulation, proving the feasibility of the proposed schemes and a small impact on the systems' capabilities.

Introduction

Avionics integration is a goal eagerly pursued by aircraft operators as it minimizes the size, weight, power and cost (the so-called SWaP-C requirements) of avionic equipment, which can translate to significant savings in their operating costs. Along these lines, this work studies the viability of integrating into a single piece of hardware: a Mode S Transponder, Automatic Dependent Surveillance-Broadcast (ADS-B) transmitting and receiving devices, and a multichannel Distance Measuring Equipment (DME). These three systems operate in the Aeronautical Radio Navigation Services (ANRS) band from 960 to 1215 MHz, and therefore, the radiofrequency analog component of the integrated system is fully shared by all the services. Other communications systems such as the L-band Digital Aeronautical Communication System (LDACS) in Europe and the Universal Access Transceiver (UAT) in USA, which operate in the same frequency band, are beyond the scope of this work, because it is not clear that their use will extend outside their current coverage areas, although their potential for future integration is briefly discussed wherein noteworthy.

The paper presents an architectural and operational design of such an integrated system. The functional system integration keystones are: 1) The Software Defined Radio (SDR) concept, 2) a Time Domain Multiple Access (TDMA) technique for sharing the High Power Amplifier (HPA), and 3) Time-Division Duplexing (TDD) to separate the transmitted and received signals.

SDRs represent a significant improvement in terms of SWaP-C minimization. Through SDRs, the Analog-to-Digital Converter (ADC) is placed as close as possible to the antenna, therefore all the traditional hardware components of the analog transceiver are implemented in software. SDRs add an extremely appealing feature to the system: Any future modernization can be deployed by means of a software update in record time and cost. In the proposed architecture, the entire ARNS band is digitized, which enables to receive any set of signals with arbitrary carrier frequencies and bandwidths. However, a first analog down conversion is required previous to the ADC due to technology requirements. On the transmitting part of transceiver, however, there is no need for a similar up conversion, and the Digital-to-Analog Converter (DAC) can almost directly feed the High Power Amplifier (HPA).

The second keystone as enumerated above is TDMA. However, herein the word "Access" in the acronym TDMA makes reference to access to a shared HPA, as opposed to access to a shared frequency channel which how this term is most commonly used. In the proposed integrated architecture, the HPA is shared by all the subsystems. This allows a significant decrease in the SWaP-C requirements of the integrated system. However, most HPAs are not linear enough to allow simultaneous transmission of signals at different carrier frequencies while preventing intermodulation products from violating the spectrum masks defined in the Minimum Operational Performance Standards (MOPS). The solution proposed in this work is to hierarchize the HPA usage from the most latency-wise demanding subsystem (Mode S Transponder) to the less demanding one (DME). In other words, DME's pairs of pulses are output to the DAC only when the Mode S Transponder is silent. A statistical analysis of the MOPS fulfillment for each subsystem is developed in the paper.

Further time domain division is done at the duplexer level. The sensitivity specified in the MOPS for the receiver subsystem requires a high isolation between the transmitter and the receiver to prevent the HPA noise to degrade the sensitivity. Since the transmission and reception frequency bands overlap, the separation is spectral domain is not feasible. For instance, consider the case of the ADS-B subsystem, where both the transmitter and the receiver use the same frequency 1090 MHz. Isolating the transmitting and receiving paths in the spatial domain requires using two antennas, longer (i.e. heavier) cabling, and is not be suitable for small aircraft. Therefore, the proposed solution is to switch the antenna between the transmitter and the receiver, using half-duplex or a "push-to-talk" scheme. Again, a statistical analysis on the compliance with the MOPS requirements is carried out.

The rest of the paper is organized as follows: Firstly, an architecture for the receiver is proposed. The most limiting requirement is the dynamic range required for the ADC. Since current technology cannot satisfy this requirement, the dynamic range is compressed in the analog domain previous to the ADC. Secondly, an architecture using a single HPA is proposed for the transmitter. A TDMA technique is proposed to share the HPA by all the services, and its feasibility is analyzed through software simulation. Following the transmitter, the focus in put on the duplexer design. TDD appears as the most suitable duplexing technique, as compared to frequency or space division duplexing. The impact of TDD on the performance of the transponder, the DME and the ADS-B transmitting and receiving devices is studied using software simulations. Finally, the conclusions of the work are presented.

Receiver Design

As regards the receiver, this work's objective is to exploit the concept of SDR [1] to design a receiver as close as possible to the ideal one, as represented in Figure 1. In this receiver, the incoming signal is sampled directly at Radio Frequencies (RF), using a technique known as Direct RF Sampling (DRFS). DRFS can be implemented either through Nyquist sampling, by sampling at least at twice the highest frequency (at least 2430 MHz), or using bandpass sampling. Note that the bandpass filter is required even for Nyquist sampling in order to avoid considering any out-of-band signal in the design, e.g. in terms of dynamic range.

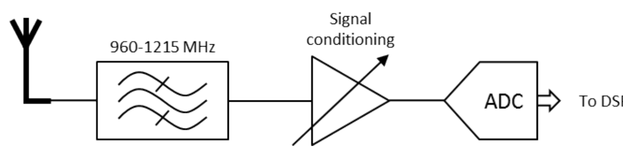

Figure 1. Software Defined Radio Architecture

Regarding bandpass sampling, the sampling frequency needs to satisfy two conditions: 1) To be greater than at least twice the sampling rate, and 2) To avoid aliasing of the frequency band. In [2] we detailed and algorithm to compute the minimum sampling rate satisfying both conditions, which for the ARNS band yields $f_s \geq 607.5$ MHz. However, lower sampling rates can be used at the cost of aliasing the unutilized edges of the ARNS band.[1] For example, a sampling rate $f_s = 485.5$ MHz allows DRFS in the band 971-1213.75 MHz.

Since DRFS eliminates the need of an analog frequency conversion, it is our preferred architecture for the near future. Unfortunately, current ADCs lack the required dynamic range in order to comply with the MOPS. Next section is devoted to the analysis of this requirement and explores different solutions providing a rationale for the receiver architecture.

Dynamic Range

The greatest challenge of the receiver for the proposed architecture lies on digitizing the bandwidth

[1] However, the proposal of EUROCONTROL for future communications system L-DACS2 is allocated within the 960-975 MHz band [3]. On the contrary, the US system Universal Access Transceiver (UAT) [4], has its 60 dB bandwidth between 974.75 and 981.25 MHz.

of interest with enough dynamic range. Enough dynamic range means that the receiver must be able to process a full-scale (maximum level) signal at any frequency channel while maintaining the sensitivity to any other signal within the band. Therefore, it is convenient to review the MOPS for the systems of interests as regards the maximum level and sensitivity requirements.

Table I gathers these parameters and reveals that the ADC must allow for input signal levels ranging from 0 dBm down to −84 dBm. In practice, some margin needs to be allocated on top, to prevent saturation, and on bottom, to receive the weakest signals with enough Signal to Noise plus Interference Ratio (SINR) to meet the other performance requirements. This requires that the ADC exhibit a practical dynamic range about 100 dB, from 3 dBm to −97 dBm. In order to determine the feasibility of this requirement, some state-of-the-art ADCs [8, 11] are represented in Figure 2, which plots the spurious and 1-MHz noise levels vs. sampling frequency. The curves have been computed using an ADC full-scale level of 3 dBm. Two different areas have been distinguished referring to the sampling technique considered, DRFS and I/Q (or complex) Sampling, "IQS". When determining the ADC performance, the frequency band considered for the input signal is the ARNS band when the DRFS technique is considered, but it is from DC to 300 MHz when I/Q sampling is used. That is why the same ADC can show different performance depending on the sampling technique used, i.e., the AD9680 at 500 MHz sampling rate. Moreover, the target level −97 dBm (spurious signals and noise from ADC should locate below this level) and the thermal noise floor −114 dBm/MHz (25 °C, receiver noise factor $F = 0$ dB) have been included for reference.

Table I. Maximum Level and Sensitivity

Service	Maximum Level	Sensitivity	Reference
Transponder	−21 dBm	−74 dBm	[5]
ADS-B	0 dBm	−84 dBm	[6]
DME	−10 dBm	−83 dBm	[7]

Two main conclusions can be extracted from Figure 2.

- None of the sample ADCs achieves the required performance.
- In general, the spurious level is the most limiting criterion, about 10 dB above the noise level. However, the noise level increases about 6 and 8 dB for the ADS-B and the transponder systems because of their wider reception channels.

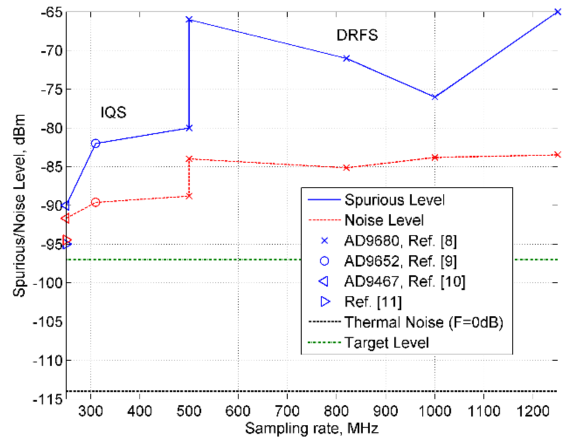

Figure 2. State-of-the-Art ADC Performance

Excluding the ADC prototype described in [11], the best case corresponds to a 250-MSPS 16-bit ADC, which attains a spurious level under −90 dBm. Recalling Table I, this result would be enough if the ADS-B receiver were not taken into consideration. In effect, excluding ADS-B decreases the full-scale level to −7 dBm, and thus, the spurious level below −100 dBm. This is the rationale followed in the next section for the proposed architecture.

Proposed Architecture

To recapitulate, the required dynamic range can be attained using I/Q sampling and processing the ADS-B signal separately. In order to extract the ADS-B from the received signal, the use of a notch filter tuned at 1090 MHz is proposed, as shown in Figure 3. In this architecture, the DME and the transponder signals go through the notch filter. On the contrary, the ADS-B signal is reflected back to the circulator, which redirects it towards the lower branch of the diagram. Then, after adjusting the power levels in both branches, the two RF signals are combined again into a single one. Some precautions must be taken in the selection of the notch filter, whose scattering parameters S_{11} and S_{21} represent both transfer functions (for the ADS-B and the rest of the band signals, respectively). Usually, the S_{11} parameter is preferred to be low enough for the band of interest, and its variation over frequency is not relevant as long as it remains low. In addition, the architecture proposed creates multiple signal paths that, if the different path delays are not controlled, can create multipath effects. Furthermore, the gain of the ADS-B branch cannot be set much higher than in the upper branch. Otherwise, the noise floor in the ADS-B branch may limit the dynamic range in the rest of the band. A good practice is to limit the gain in both branches so that the noise level locates slightly above the spurious level of the ADC. The second bandpass filter process is intended to remove harmonic distortion from the amplifiers, and may not be required.

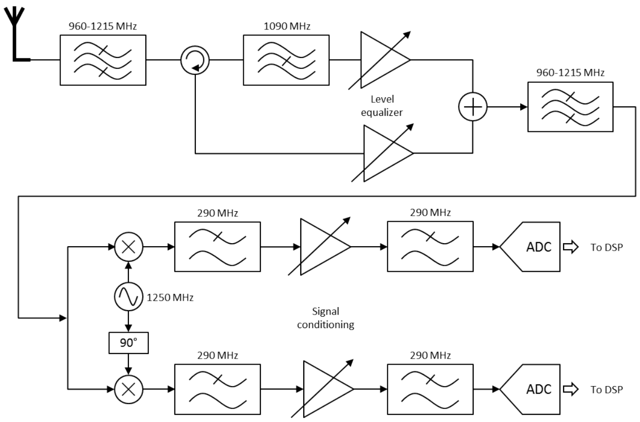

Figure 3. Receiver Architecture

Once the dynamic range has been compressed in the upper part of the architecture, the lower part implements the I/Q sampling technique. This technique has been selected because the sampling frequency, 250 MHz, is less than the minimum required for DRFS. In the architecture in Figure 3, the motivation of the second low-pass filtering stage is to eliminate harmonic distortion from the amplification stage and may not be required.

The selection of the local oscillator frequency has been done by considering the intermodulation products generated at the output of the mixer. Figure 4 shows the spectrum allocation at the output of the mixers when a local oscillator frequency $f_{OL} = 1250$ MHz is used. The maximum frequency in the band of interest is located at 290 MHz, while the minimum frequency of the unwanted intermodulation products is 670 MHz. This provides enough spectral separation for the low pass filters to efficiently remove the unwanted frequency bands.

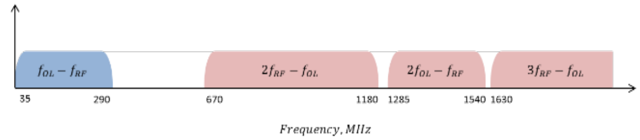

Figure 4. Spectrum at the Output of the Mixer

On the other hand, since the bandwidth of the ARNS band, 255 MHz, is slightly bigger than the sampling frequency, 250 MHz, a slight overlap of 5 MHz at the edges of the band is produced by the sampling process. This is shown in Figure 5. Note that the ARNS spectrum has been inverted in the frequency down conversion process. This aliasing can be avoided by overclocking the ADC conveniently. However, the only service that actually uses the lower edge of the band is the European L-DACS2 communications system, whose standardization and approval have not been realized yet. Therefore, it might be possible that the aliasing of the band did not have any impact in the receiver. Nonetheless, for the sake of future flexibility, using a higher sampling frequency is the best option.

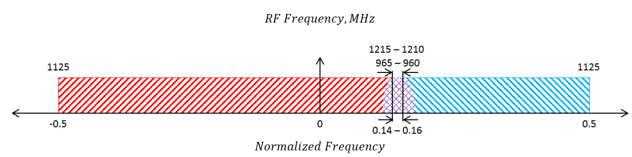

Figure 5. Aliasing of the ARNS Band

Transmitter Design

As opposed to the receiver, DRFS (here, the "S" stands for Synthesis) is possible with current technology thanks to the lower dynamic range requirements and better performance of DACs as compared to ADCs. The proposed architecture for the transmitter is shown in Figure 6. The dynamic range requirements are given by the spectrum mask and maximum transmitted power, and shown in Table II. In this case, the ADS-B transmitting device is the transponder itself. It is not difficult to find commercial DACs satisfying the required spurious level. When not transmitting, the emission of spurious RF energy is controlled by switching off the HPA.

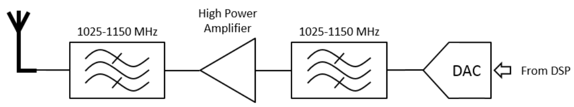

Figure 6. Transmitter Architecture

Table II. Minimum Peak Power and Maximum Out-of-Band Emissions

Service	Minimum Peak Power	Out-of-Band Emissions	Reference
Transponder	51/49 dBm	60 dBc	[5]
DME	54/47 dBm	38 dBc	[7]

TDMA Feasibility

As shown in Figure 6, the integrated DME and transponder (with ADS-B capabilities) transmitter share a common High Power Amplifier (HPA). Allowing for simultaneous transmission of signals at different carrier frequencies would require a highly linear HPA in order to prevent third-order intermodulation products within the transmission band. Such an HPA cannot be found easily or is not practical. Since the third-order intercept point (IP3) is typically 10 dB above the 1-dB compression point, a spurious emission level of 60 dBc would require to transmit at least 20 dB below the 1-dB compression point. That means that the maximum power of the HPA would locate in the order of 80 dBm.

The approach proposed here is to implement a Time Domain Multiple Access (TDMA) technique for the shared use of the HPA. This guarantees that only one input signal is transmitted at each time, and the out-of-band emissions are kept under the 60 dBc target. The TDMA technique is implemented in the digital domain using a simple "first-come, first-served" policy. Thus, if the HPA in not in use, services can make use of it in exclusivity until their transmission has ended. Otherwise, services abort their current transmission. In case two or more services want to reserve the HPA at concurrent times, the priority is granted in this order: transponder, ADS-B, and DME. Moreover, the transponder takes control of the HPA right after an interrogation is received, but if the HPA is in use, it keeps trying until the time the transmission starts, at which the transmission is aborted if the HPA has not been released.

The proposed TDMA scheme has been evaluated through software simulation in order to assess the probability of successful transmissions by each service. Table III shows the resulting probability of successful transmission for the different services considered. These probabilities have been computed using random interval between transmissions, with Pulse Repetition Frequencies (PRFs) ranging from 125 to 150 Hz for the DME, 50 and 75 Hz for Mode S interrogations, 1000 and 1200 Hz for Air Traffic Control Radar Beacon System (ATCRBS) interrogations, and 5 and 10 Hz for ADS-B transmissions. Since these values are higher than those used normal operation, the results are, in this sense, pessimistic[2]. Moreover, the analysis assumes that all the interrogations to the transponder trigger a reply and only the cases in which the transponder and the DME interfere with each other are considered. For instance, the case when a Mode S interrogation cannot be replied because the transponder is already replying an ATCRBS interrogation or transmitting an ADS-B message is not considered as a failed transmission. The results reveal a very low impact from sharing the HPA in the successful transmission rate of all the systems, and consequently, the feasibility of the architecture proposed for the transmitter. Additionally, the goal in this section is to study the capability of the transmitter to reply during peak interrogation rates. Therefore, the transponder interrogations are simulated as though the radar is continuously aimed to the aircraft. Next section provides a more realistic analysis, which considers the rotation of the radar antenna, as well as the impact of the transmitter in the reception of interrogations.

Table III. Successful Transmission Rate for the Proposed TDMA Technique

Service	Successful Transmission Rate
Mode S	100.0 %
ATCRBS	99.5 %
ADS-B	99.4 %
DME	92.3 %

[2] However, other services related to the transponder such as Traffic Collision Avoidance System (TCAS) or Flight Information Services (FIS) have not been included into the analysis. Given the results obtained for the pessimistic PRF values used in the simulations, we do not expect a big impact of these services in the interoperability with the DME.

Duplexer/Antenna Design

It is equally important in the design of the transceiver to determine how the transmitter and the receiver are connected to the antenna. In general, transmitted and received signals can be separated in the space, frequency or time domains. In our case, frequency separation is not possible since the transmitted signal uses the same frequency band as the received one. Separation in the space domain can be attained when the transmitter and the receiver are connected to different antennas. This approach is advantageous over time domain separation in the sense that all services will be able to receive and process their respective incoming signals continuously. From the peak power of the transmitter, 54 dBm, and the full scale level of the receiver, −7 dBm, the required isolation between the transmitting and receiving antennas should be at least 61 dB. This requires separating the antennas at least 88 m (using a typical antenna gain value, 5 dBi), which is not feasible for most aircraft. Consequently, signal separation in the time domain reveals as the best option given current technology. There are, however, some experimental works that might enable for the near future a drastic decrease in the separation of the antennae or even sharing the same antenna (see e.g. [12-14]). These approaches should be considered in future revisions of the current design.

TDD Feasibility

Let us now explore in this section the feasibility of a Time-Division Duplexing (TDD) technique for the proposed transceiver. From the previous analysis of TDMA feasibility, the percentage of time that the HPA is on, i.e., the transmitter duty cycle, can be as high as 4 %. This is compatible with the MOPS of an ADS-B receiving device, whose duty factor (i.e., the percentage of time the ADS-B receiver is able to receive and process ADS-B messages) is required to be at least 90 % when its receiver is shared with other receiving functions [6]. However, the previous analysis did not take into account that not all interrogations can be received or the rotation of the radar antenna, and in consequence, a decrease in the transmitter duty cycle can be expected.

The feasibility of the TDD approach has been studied through software simulations in which the proposed transceiver is simultaneously operating a transponder, a DME, and an ADS-B transmitting (ADS-B Out) and receiving (ADS-B In) devices. The transponder is being interrogated by a Mode S Secondary Surveillance Radar (SSR) with random PRF between 50 and 75 Hz, and an ATCRBS SSR with random PRF between 1000 and 1200 Hz. Both SSRs interrogate the transponder only during the dwelling interval, which simulates an antenna rotating at 15 rpm with a beam width of 5°. The DME is interrogating one ground station with random PRF between 125 and 150 Hz. The ADS-B Out component is broadcasting messages with random PRF between 5 and 10 Hz. As regards ADS-B In, 100 sources are simulated each broadcasting with random PRF between 5 and 10 Hz as well. An ADS-B message, SSR interrogation or DME reply is considered successfully received and processed if the antenna is not switched to transmission mode throughout its duration. For the transponder, the antenna is switched to transmission mode as soon as an interrogation is successfully received. For the DME and ADS-B Out, switching is done at the time of transmission. Once a transponder reply, a DME interrogation, or an ADS-B message have been transmitted, the antenna is switched back to reception mode.

Table IV shows the simulated success rate of the proposed transceiver using TDD. Several success criteria have been considered for the ease of comparison with different reference installations. In Criterion A, only the interference between the DME and the rest of services is considered. The motivation is to show the relative success rate as compared with a reference installation in which the DME utilizes independent equipment that can transmit and receive simultaneously to the transponder and the ADS-B equipment. However, the ADS-B receiving device of the reference installation is not supposed to properly process messages received at the same time of a transponder reply or ADS-B Out message. Therefore, only when the DME affects the proper functioning of the transponder and ADS-B, or vice versa, is considered as a failure. The numbers in the second column of Table IV show that success rate is almost not affected, with only the ADS-B In service reducing its rate below 99 %, down to 97.6 %.

Table IV. Success Rate for the Proposed TDD Technique

Service	A	B	C	D	E
Mode S	99.1 %	99.4 %	98.9 %	98.9 %	91.6 %
ATCRBS	99.1 %	99.1 %	99.2 %	99.1 %	97.7 %
ADS-B Out	99.5 %	99.4 %	99.3 %	99.5 %	99.3 %
ADS-B In	97.6 %	97.3 %	95.0 %	90.8 %	90.0 %
DME	99.5 %	99.5 %	95.4 %	92.2 %	99.5 %

The reference installation used for Criterion B is such that the ADS-B receiving device is able to process incoming ADS-B messages even when a transponder reply or an ADS-B message is transmitted. Therefore, all cases in which the ADS-B reception was not successful due to an antenna switching to transmission are taken into account. The third column of Table IV shows the success rate under this criterion, and the ADS-B In service is practically not affected by the transmissions of the transponder.

Scenarios named "C" and "D" are actually an extension of Criterion B, in which the SSR antennas are not rotating but continuously interrogating the transponder at the specified rates. The motivation is to show the success rate of the different services during the dwelling times. Thus, in Scenario C the Mode S SSR is continuously interrogating the transponder, while in Scenario D, the ATCRBS SSR is, in addition to Mode S SSR, continuously interrogating the transponder as well. However, the interrogation PRF range of the ATCRBS SSR has been reduced in Scenario D to 250 and 300 Hz. In both scenarios, the DME and the ADS-B In services can successfully operate during peak interrogation conditions above 90 % compared to the reference installation in which none of them are perturbed by the transponder. We estimate these percentages high enough to consider the implemented TDD technique suitable even during peak-interrogation intervals.

Finally, Criterion E is used to show the "raw" success rate for all the services. Under this criterion, any interruption in the proper reception of a transponder interrogation, DME reply, or incoming ADS-B message (even due to overlap with another incoming ADS-B message) is considered as non-successful. As in previous cases, the incapability to transmit because the HPA has been assigned to other service is also considered as non-successful. The SSR only interrogate the transponder during the dwelling intervals. As can be seen in Table IV, the success rate is kept for all services above 90 %, which satisfies the MOPS of this equipment and proves the feasibility of TDD for the proposed integrated transceiver. In this scenario, the average duty cycle of the transmitter is 2 %, which is lower than the peak value obtained in the analysis of the TDMA technique, since the transponder is interrogated only during the dwelling interval.

Conclusion

The future of the ARNS band is at a critical point in which current CNS systems have not proved their operability for estimated increase in future air traffic density. Among the motivations of there is the consideration that providing avionics with the necessary flexibility for future CNS standards is imperative. In addition to this, the exploitation of the SDR concept for avionics equipment promises to drastically reduce the cost associated to the design, implementation, deployment and maintenance of current and future avionic systems.

This work is devoted to the design of the main impediment to the application of SDR to avionics: the analog transceiver. Specifically, a transceiver for the ARNS band has been fully architected. The design satisfies the dynamic range requirements to meet the specification in the MOPS of the transponder, the DME, and the ADS-B equipment. A TDMA technique for sharing the HPA, and therefore minimizing the SWaP-C requirements, has been proposed and proved its feasibility. TDD has revealed as the most suitable technique for the duplexer and its compliance with the MOPS has been shown.

However, some limitations of the state-of-the-art technology have conditioned the design. Consequently, the proposed design needs to be revised with future technological advances. For instance, the need to compress the dynamic range in the analog domain will become unnecessary when future ADCs provide the required dynamic range. Additionally, ongoing research on transmitted signal cancellation in the duplexer might provide enough isolation to substitute the TDD approach.

Our ultimate goal is to provide avionic equipment with the flexibility required to operate in a multi-standard paradigm. This will enormously facilitate the transition to a hypothetical modernization of CNS standards in order to accommodate future needs.

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